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Solar Radiation and Illumination

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SOLAR RADIATION AND ILLUMINATION

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ABSTRACT

Experimental data were collected and analyzed under various cloud cover conditions to establish the relationship between solar irradiance and illuminance. Empirically derived equations are presented for estimating diffuse and total illuminance as a function of total and diffuse solar radiation.

Key words: daylighting; illuminance; illumination; irradiance; solar radiation

Table of Contents

1. INTRODUCTION

Illumination conditions, both outdoors and indoors, are of interest in building design and energy analysis. Except for clear and completely overcast sky conditions, very few data are available concerning levels of outdoor illuminance under realistic sky conditions. Under the randomly changing outdoor illuminance levels frequently encountered, it is difficult to obtain an accurate prediction of daylighting conditions. Various procedures have been proposed and utilized for predicting outdoor illuminance levels; some are based on fundamental principles of atmospheric science [1] while others use empirical relationships [2,3]. These procedures vary in complexity and accuracy and require a variety of input parameters from which illuminance levels are calculated. The accuracy of many of these procedures has not been validated for a complete range of illumination conditions.

Many building design and energy analysis procedures provide irradiance information, either from weather data tapes or from calculation. Thus, correlations between solar radiation conditions and the resulting illumination conditions would enable outdoor illumination levels to be calculated. Since illuminance (visible light, e.g., C.I.E. photopic response ~ 0.38 to 0.78 μm) is largely dependent upon irradiance (full-spectrum solar radiation ~ 0.2 to 3 μm) it was desirable to establish a procedure for calculating illuminance as a function of irradiance.

While the measured outdoor illuminance data are limited in scope and in available locations, large amounts of solar radiation data are available from data routinely recorded at weather stations throughout the country for many years.

It has been customary to relate the illuminance to the total irradiance in terms of luminous efficacy, which is defined as follows:

$$\eta = \frac{K_m \int_{0.380}^{0.780} V(\lambda)E(\lambda)d\lambda}{\int_{0}^{\infty} E(\lambda)d\lambda}$$

where

K_m = maximum spectral luminous efficacy or luminosity factor = 680 ℓm/w

$V(\lambda)$ = standard relative luminous efficacy of monochromatic radiation of wave length λ

$E(\lambda)$ = monochromatic solar spectral irradiance

Several researchers have published the values of η for selected and typical sky conditions. W. Chroscicki [4], for example, developed the following equation for clear sky.

$$\eta = 59.3\ h^{0.1252} \qquad \ell m/w$$

where

h = solar altitude angle in degrees.

Rosenfeld and Selkowitz [5], on the other hand, suggest $\eta = 106 \pm 2$ ℓm/w for the direct solar component and 116 ± 7 ℓm/w for the diffuse sky component for clear sky conditions.

For the cloudy sky, Krochmann [6] suggests an approximate value of 115 ℓm/w.

While these solar luminous efficacy data are affected by the presence of atmosphere and cloud cover, the extraterrestrial data have been estimated as 93.7 ℓm/w [7].

None of the data presented above permit the evaluation of outdoor illumination under partially cloudy conditions which prevail during the course of a year, and which are very important for the annual energy analyses.

Shikuyu and Kimura [8] have presented a relation to combine the Chroscicki equation with Krochmann data in conjunction with cloud amount factor, C_F, which ranges from 10 for a completely cloudy sky to 0 for a clear sky as recorded by meteorological stations. The suggested equation is

$$\eta = 115\ \left(\frac{C_F}{10}\right) + 59.3\ h^{0.1252}\ \left[1 - \frac{C_F}{10}\right]$$

The disadvantage of this equation is that the cloud amount parameter C_F is very subjective to the observer and not well defined.

An alternative cloud amount factor is utilized in this paper based upon the ratio of observed diffuse and total solar radiation levels. This new cloud amount factor is then used to compute the luminous efficacy of a cloudy sky.

2. SOLAR RADIATION AND ILLUMINATION

Solar radiation at the earth's surface is composed of two components, diffuse and direct. Various combinations of diffuse and direct irradiance occur due to different sky conditions. The sum of diffuse and direct irradiance equals total irradiance. Under completely overcast conditions, diffuse irradiance is equal to total irradiance, while under very clear sky conditions the diffuse component is approximately 10 percent or less of the total irradiance. The ratio of diffuse to total irradiance can be described as the cloud ratio, or:

$$\text{Cloud Ratio} = CR = \frac{\text{Diffuse Irradiance}}{\text{Total Irradiance}} = \frac{I_d}{I_T} \qquad (1)$$

Similarly, outdoor illuminance is composed of diffuse and direct components. Traditionally, in the daylighting community, diffuse illuminance is of interest, since it represents visible light from the sky, enabling indoor illuminance to be subsequently calculated. Most interior locations do not receive direct irradiance or illuminance, since the sun is usually not visible through the window. In those cases where direct irradiance (and consequently direct illuminance) is present, it is usually viewed as being undesirable, from the standpoint of glare and occupant comfort. Under these conditions, frequently a shade or other sun control device is utilized.

The direct and total illuminance components are of interest when determining the level of illumination incident upon an exterior surface (such as the ground or a building), when skylights are considered, or when reflective louvers are used to bring the direct beam illumination deep indoors.

Since solar illuminance is a portion of the full solar spectrum, illuminance and irradiance levels are obviously related. The relative contributions of the ultra-violet, infrared, and visible portions of the solar spectrum vary with different atmospheric conditions. Thus the level of irradiance may change while the illuminance remains constant, due to a change in the intensity outside of the visible spectrum.

Measurements were made of the levels of total irradiance and illuminance on a horizontal surface, along with concurrent measurements of diffuse irradiance and illuminance. The diffuse components were measured using shading bands. (See figure 1). These measurements were made at the NBS daylight research facility near Washington, D.C. (~ 39° lat.).

3. DIFFUSE ILLUMINANCE

Earlier measurements of diffuse illuminance indicated a strong sensitivity to sky condition [9]. Diffuse illuminance levels were low for clear skies and completely overcast skies. Highest diffuse illuminance levels occurred under partially overcast conditions, when the sun was relatively unobstructed and the remainder of the sky cloudy. Overcast conditions produced the highest levels of diffuse illuminance per unit total irradiance, but total irradiance levels were usually low at these conditions.

Analysis of the measured data indicated two possible procedures for calculating diffuse illuminance based on irradiance data. The simplest method requires a correlation between measured levels of diffuse irradiance and diffuse illuminance. Figure 2 presents a plot of diffuse illuminance as a function of diffuse irradiance. From this plot, it is seen that diffuse illuminance can be calculated using the following relation:

$$E_d = 119 \cdot I_d \tag{2}$$

where

E_d = diffuse illuminance (lux)

I_d = diffuse irradiance (Wm^{-2})

Equation 2 indicates a luminous efficacy for diffuse illumination of 119 lumens/watt. A comparison of measured diffuse illuminance versus calculated (from eq. 2) is presented in figure 3.

The average calculation error for the sample day presented is 7 percent, with the greatest error occurring at the lower illuminance levels. On this sample day, solar radiation and sky condition covered a large range.

The second method for calculating diffuse illuminance is based on a correlation of that parameter with total irradiance and cloud ratio. Due to the wide variations in sky condition, diffuse illuminance does not vary directly with total irradiance, as shown in figure 4. However, if the cloud ratio is known, or can be estimated, this information can be combined with information concerning the level of total irradiance to calculate diffuse illuminance.

Figure 5 presents a typical plot of diffuse illuminance as a function of total irradiance for different types of sky conditions. Large increases in total irradiance cause only small increases in diffuse illuminance under clear skies, while under overcast conditions diffuse illuminance changes dramatically with total irradiance.

Figure 5 suggests that for a fixed cloud ratio, diffuse illuminance can be represented as a function of total irradiance in the form:

$$E_d = M \cdot I_T \tag{3}$$

where

I_T = total irradiance (w/m^2)

The value of the slope M would be dependent upon the cloud ratio at that particular time.

Combining equations 1 and 2 enables a correlation between diffuse illuminance and total irradiance and cloud ratio to be obtained as follows:

$$E_d = 119 \cdot I_d \cdot \frac{I_T}{I_T}$$

$$E_d = 119 \cdot \frac{I_d}{I_T} \cdot I_T$$

$$E_d = 119 \cdot CR \cdot I_T \tag{4}$$

From eq. (4) the slope M in eq. (3) is seen to be equal to 119 CR.

To investigate the accuracy of eq. (4) the relation between measured diffuse illuminance and total irradiance was examined.

Figures 6a through 6o present measured diffuse illuminance as a function of total irradiance for the full range of cloud ratios. Fifteen groups of points are plotted, each corresponding to a small range of cloud ratios as labeled. A least-squares best-fit line forced through zero is also drawn for each plot. Diffuse illuminance is seen to vary linearly with total irradiance for each fixed cloud ratio range, as would be predicted by eq. (4). The slope of each least-squares plot should agree with the slope predicted by eq. (3), namely:

119 • CR should equal slope of least-squares line for each range of cloud ratios.

This comparison is made in Table 1, and good agreement is seen, considering that the least-squares calculations are based on points obtained for a range of cloud ratios.

The accuracy of diffuse illuminance values calculated using eq. (4) would be the same as that using eq. (2), since in each case the level of diffuse irradiance, or the cloud ratio, is known. However, the level of diffuse irradiance is not always known. If a value for diffuse irradiance is not available, it may be possible to estimate the percentage of cloud cover to

enable subsequent calculation of diffuse illuminance using eq. (4). The U.S. weather service records a "cloud cover factor", which is an estimate of cloud cover. While this procedure has not been evaluated in this report, it may be possible to convert the value of cloud cover factor to cloud ratio for use in calculating the diffuse illuminance using eq. (4).

Table 1
Calculated Slope* versus
Measured Slope**

Cloud Ratio Range	Average Cloud Ratio	Least-Squares Slope	Calculated Slope $= 119 \cdot CR$
$0.90 < CR \leq 1.0$	0.966	111	115
$0.80 < CR \leq 0.90$	0.857	101	102
$0.70 < CR \leq 0.80$	0.750	85	89
$0.60 < CR \leq 0.70$	0.651	81	77
$0.50 < CR \leq 0.60$	0.547	74	65
$0.45 < CR \leq 0.50$	0.475	65	57
$0.40 < CR \leq 0.45$	0.430	56	51
$0.35 < CR \leq 0.40$	0.375	47	45
$0.30 < CR \leq 0.35$	0.320	41	38
$0.25 < CR \leq 0.30$	0.271	35	32
$0.20 < CR \leq 0.25$	0.230	29	27
$0.167 < CR \leq 0.20$	0.181	25	22
$0.133 < CR \leq 0.167$	0.155	22	18
$0.100 < CR \leq 0.133$	0.112	14	13
$0 < CR \leq 0.100$	0.083	13	10

* from eq. (4)
** from fig. (5)

4. TOTAL ILLUMINANCE

The level of total illumination is most easily calculated on the basis of the level of total solar radiation. Figure 7 presents total illuminance on a horizontal surface as a function of total irradiance on a horizontal surface. The effect of variations in cloud ratio is small, producing scatter about a best-fit line:

$$E_T = 110 \cdot I_T \tag{5}$$

Equation (5) indicates a luminous efficacy for total solar radiation of 110 lumens/watt. Figure 8 compares measured total illuminance versus that calculated using total irradiance and eq. (5) for a typical sample day. The average error for the calculations is 8 percent, with the largest errors occurring at lowest illuminance levels.

The luminous efficacy of extraterrestrial solar radiation is approximately 94 lumens/watt. This radiation is composed only of a direct component since there is no atmosphere to produce a diffuse component. At the earth's surface, the intervening atmospheric layer causes some of the solar radiation to scatter, resulting in sky or diffuse radiation. Since the atmosphere transmits solar radiation preferentially in the visible region, and due to the longer path length of diffuse radiation as compared to direct radiation, the percentage of the visible component of diffuse solar radiation is greater than that of direct solar radiation. Thus the luminous efficacy of diffuse solar radiation should be greater than the luminous efficacy of direct solar radiation. Also, the luminous efficacy of direct radiation at the earth's surface would be greater than the extraterrestrial value, due to influence of the atmosphere. The luminous efficacy of direct solar radiation was estimated from the ratio of direct illuminance to direct irradiance, each of which in turn was calculated from the difference between the measured levels of total and diffuse illuminance and irradiance.

The average value for the luminous efficacy of direct solar radiation at the earth's surface was determined from measurements to be 105 lumens/watt. Considerable variation in this value can occur with different atmospheric conditions and cloud ratios, since under completely overcast sky conditions the direct irradiance component is actually completely diffused.

Since total solar radiation includes both diffuse and direct irradiance, its luminous efficacy should fall somewhere between the two. This pattern is reflected in eqs. (2) and (5), where the luminous efficacy of diffuse irradiance is seen to be greatest, while that of total irradiance falls between the values for direct and diffuse irradiance. However, the luminous efficacy of total solar radiation would vary slightly as the percentages of diffuse and direct irradiance vary. This would be the case with different cloud ratios.

The value of 110 lumens/watt efficiency for total irradiance is an average value representing all types of cloud conditions. When clear sky conditions prevail, the actual luminous efficacy would probably be slightly less. As

conditions become increasingly overcast, the luminous efficacy of total irradiance would approach that of diffuse irradiance.

The difference between the luminous efficacies of diffuse and total irradiance leads to an inconsistency concerning the correlations presented in eqs. (2), (4), and (5). When the cloud ratio exceeds 92 percent, the calculated values of diffuse illuminance will be greater than the calculated values of total illuminance, an obvious impossibility. When this situation occurs, the larger value should be used for total and diffuse illuminance, since sky conditions would be overcast, and the luminous efficacy of total irradiance would be the same, or nearly the same, as that for diffuse irradiance. Since levels of irradiance are usually low when the sky is overcast, differences between the illuminances as calculated from eqs. (2) and (5) should be small.

Another procedure can be used for calculating total illuminance which eliminates the previously described inconsistencies. Since total illuminance is composed of diffuse and direct components, E_T can be expressed by the relation:

$$E_T = E_D + E_d$$

where

E_D = direct illuminance

Using the value of 105 lumens/watt luminous efficacy for direct irradiance and eq. 2, this yields:

$$E_T = (105 \cdot I_D) + (119 \cdot I_d)$$

where

I_D = direct irradiance

Since $I_D = (1-CR) \cdot I_T$ and $I_d = CR \cdot I_T$,

$$E_T = I_T \, [105 \cdot (1-CR) + 119 \cdot (CR)]$$

This equation can be rearranged to yield:

$$E_T = [105 + (CR \cdot 14)] \cdot I_T \tag{6}$$

Equation 6 produces a weighted average between the diffuse and direct illuminance components. Thus, the luminous efficacy of total irradiance, according to eq. 6, would increase with increasing cloud ratio.

Under completely overcast conditions, cloud ratio equals one and eq. 6 reduces to eq, 2.

5. SUMMARY AND CONCLUSIONS

Levels of total and diffuse illuminance can be calculated from solar radiation data according to the following relations:

a) $E_d = 119 \cdot I_d$
b) $E_d = 119 \cdot CR \cdot I_T$
c) $E_T = 110 \cdot I_T$ for $CR < 0.92$, $E_T = E_d$ from a or b for $CR > 0.92$
d) $E_T = [105 + (CR \cdot 14)] \cdot I_T$

The average uncertainty in the calculated values is approximately 8 percent. This is due to a combination of measurement error and variations in the relative contribution of the visible band to the full solar spectrum.

The calculation procedures are sufficiently accurate to permit illuminance levels to be calculated from concurrent irradiance levels, as long as 100 percent accuracy is not required.

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Figure 1. NBS Daylight Research Facility

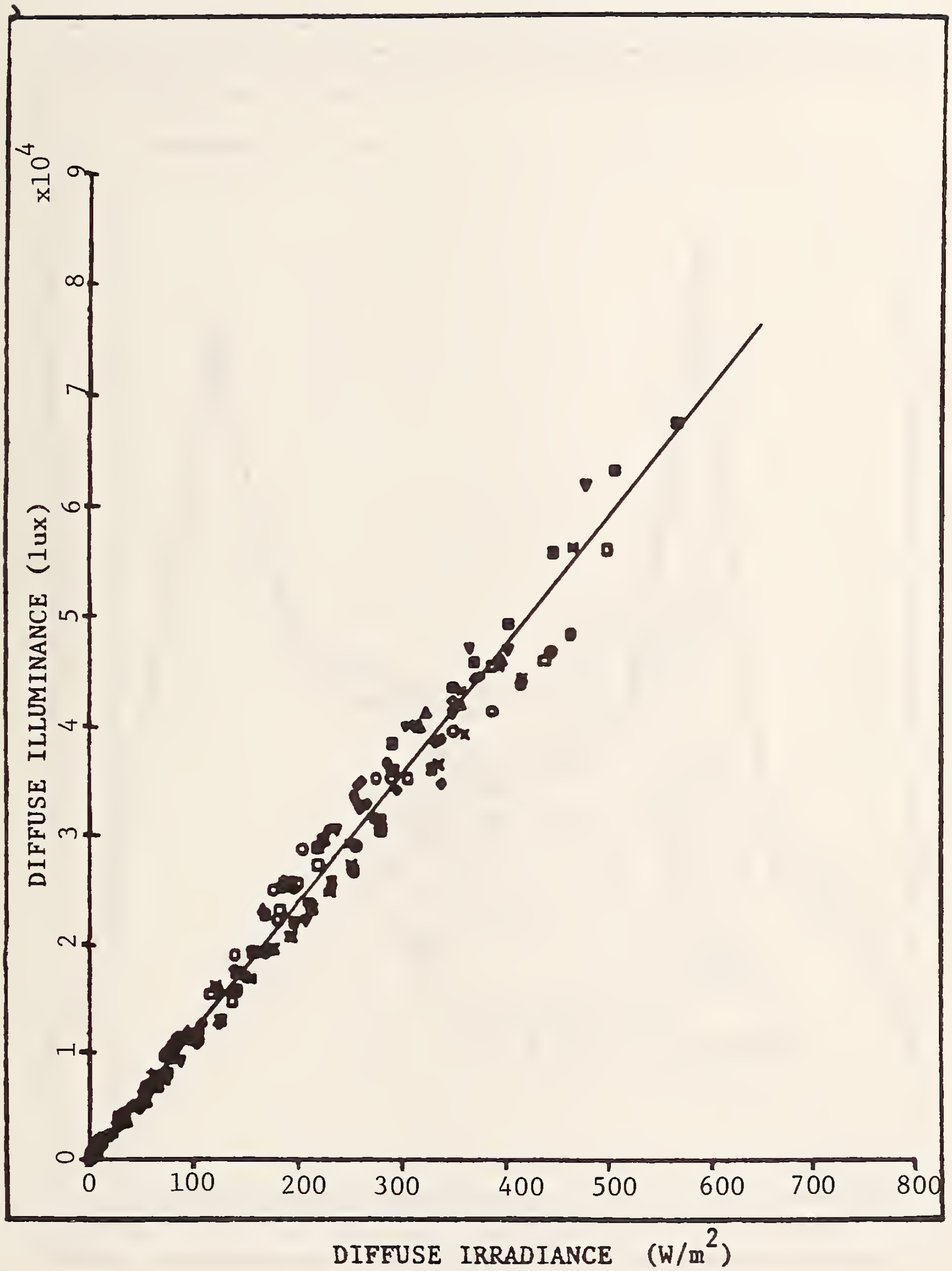


Figure 2. Diffuse Illuminance as a Function of Diffuse Irradiance

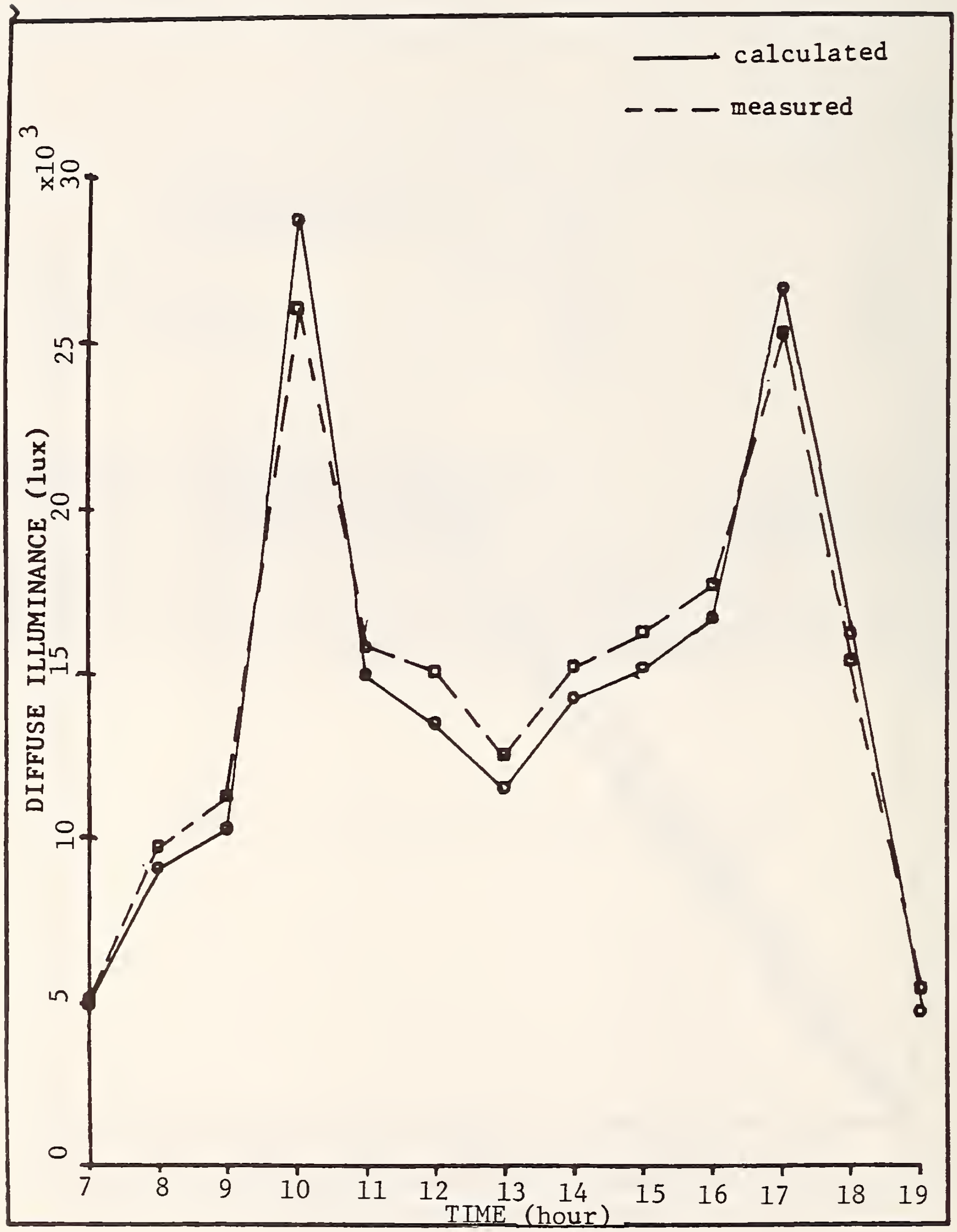


Figure 3. Diffuse Illuminance - Measured vs. Calculated

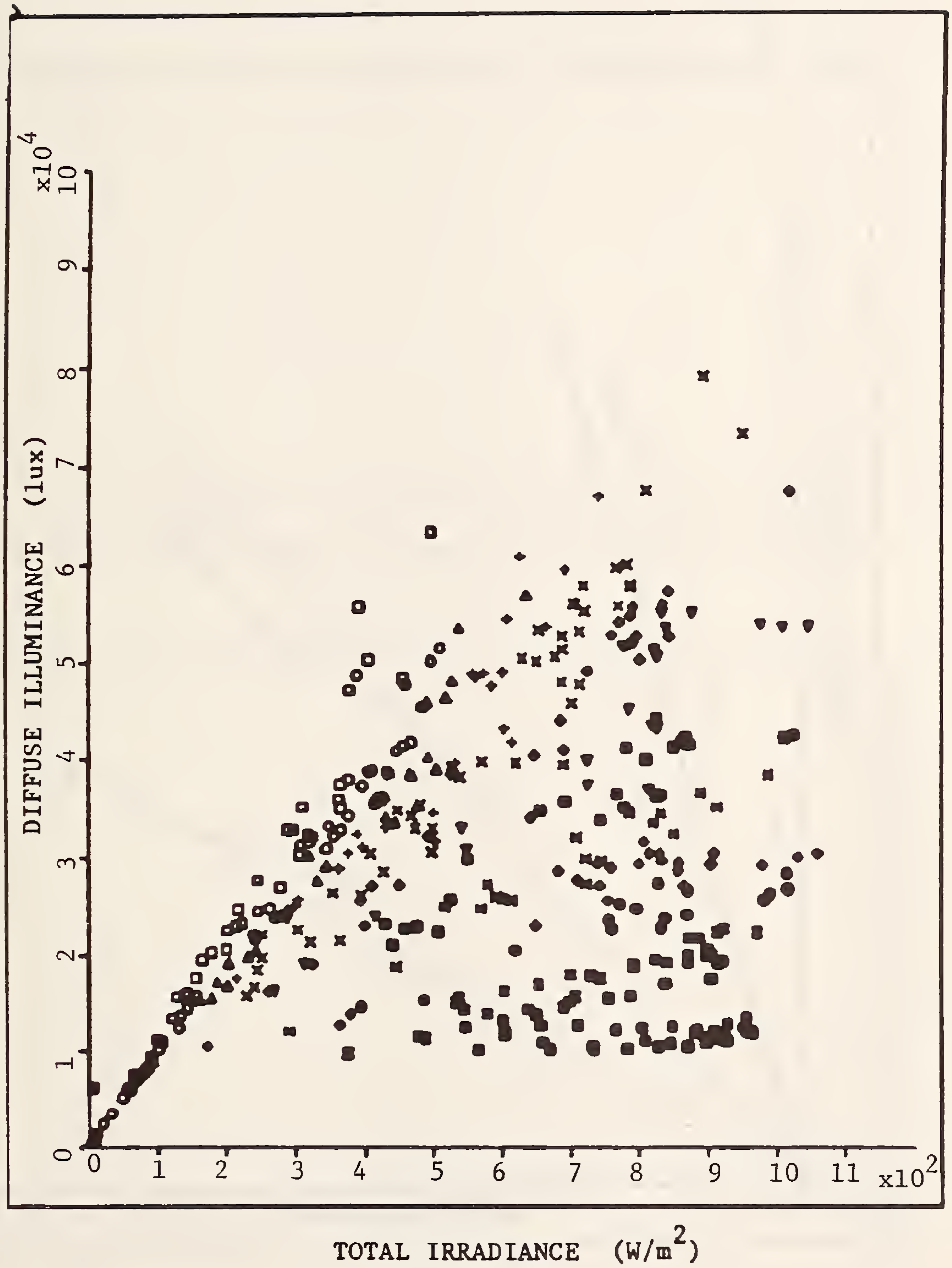


Figure 4. Diffuse Illuminance as a Function of Total Irradiance

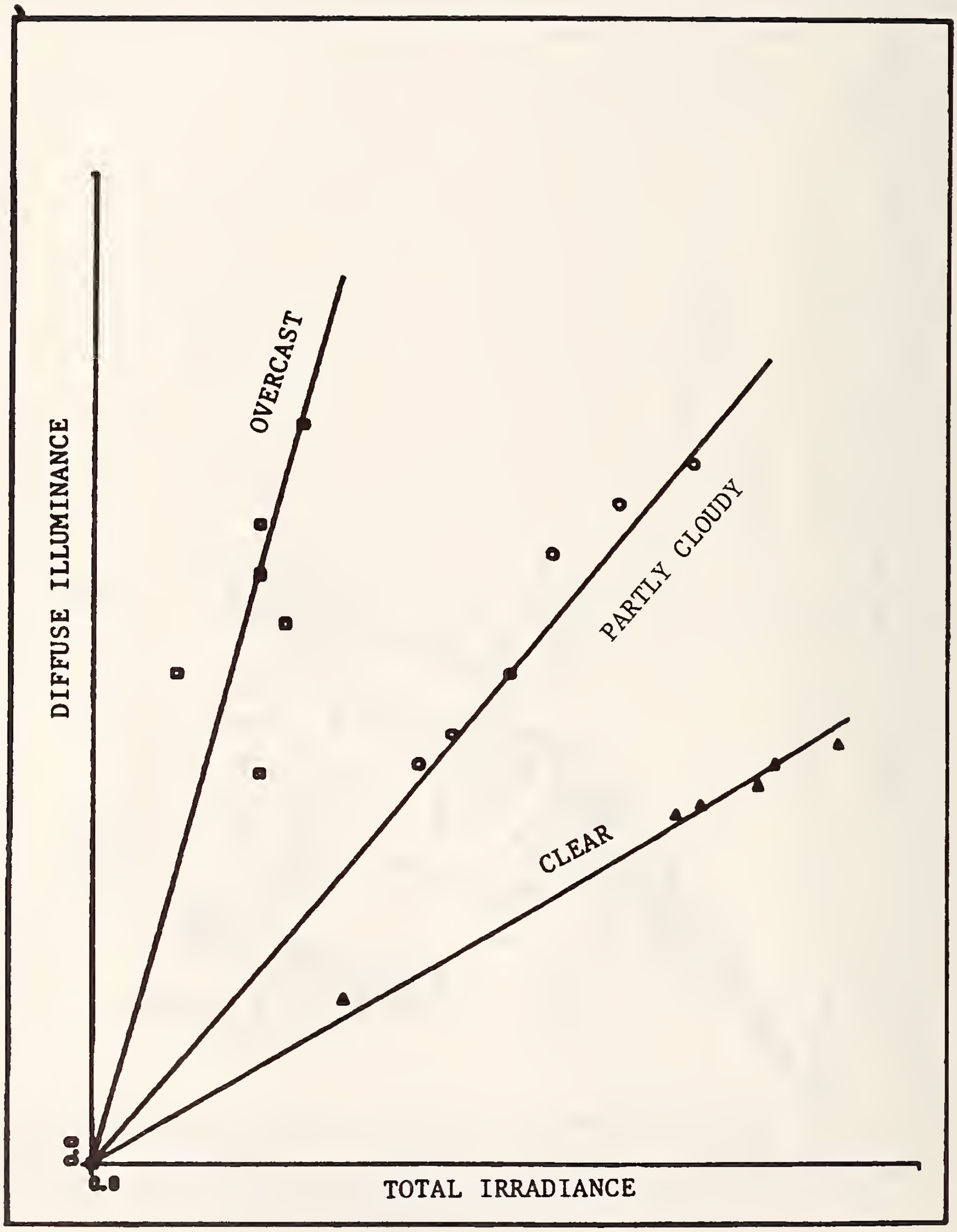


Figure 5. Characteristic Plot of Diffuse Illuminance as a Function of Total Irradiance

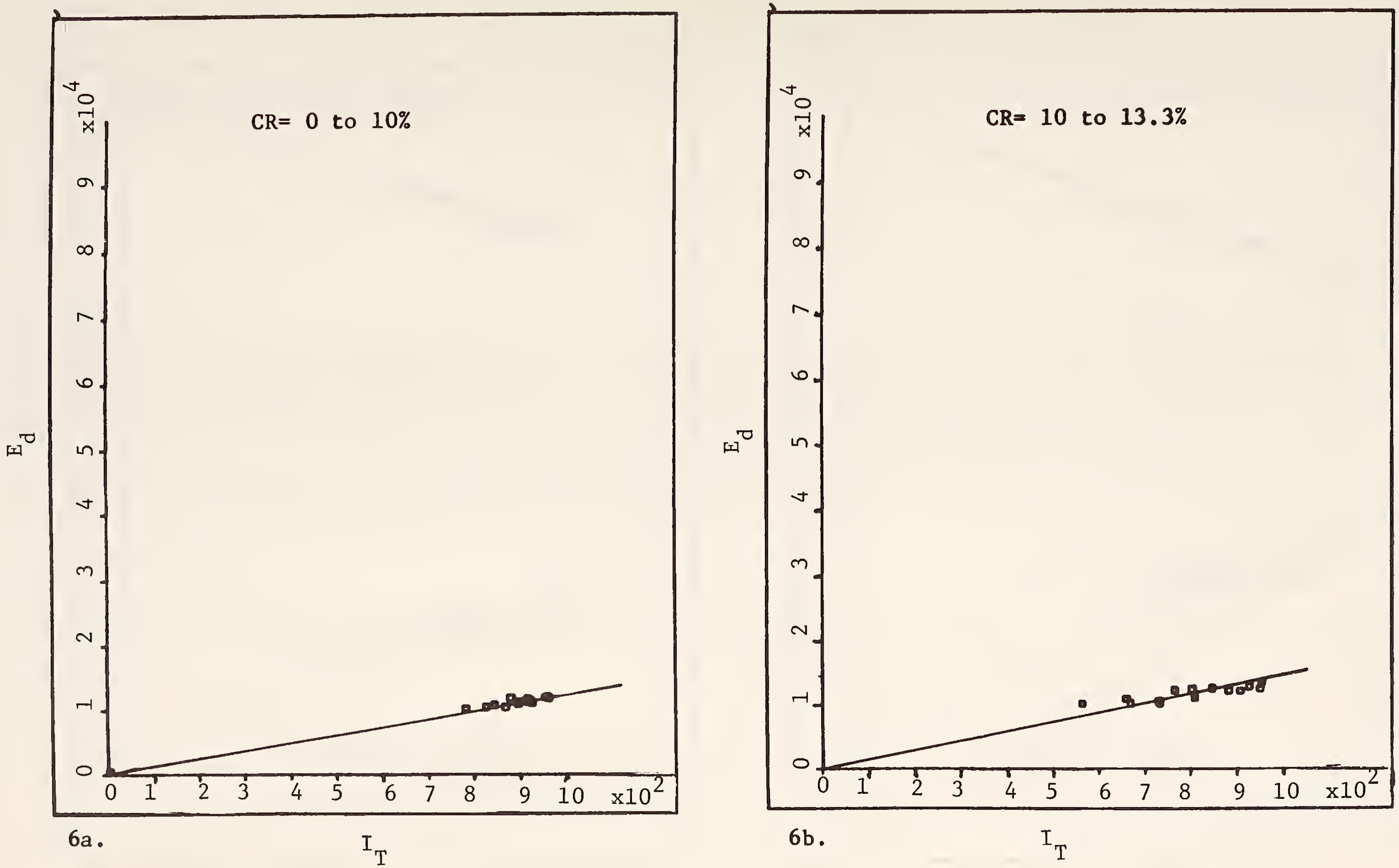
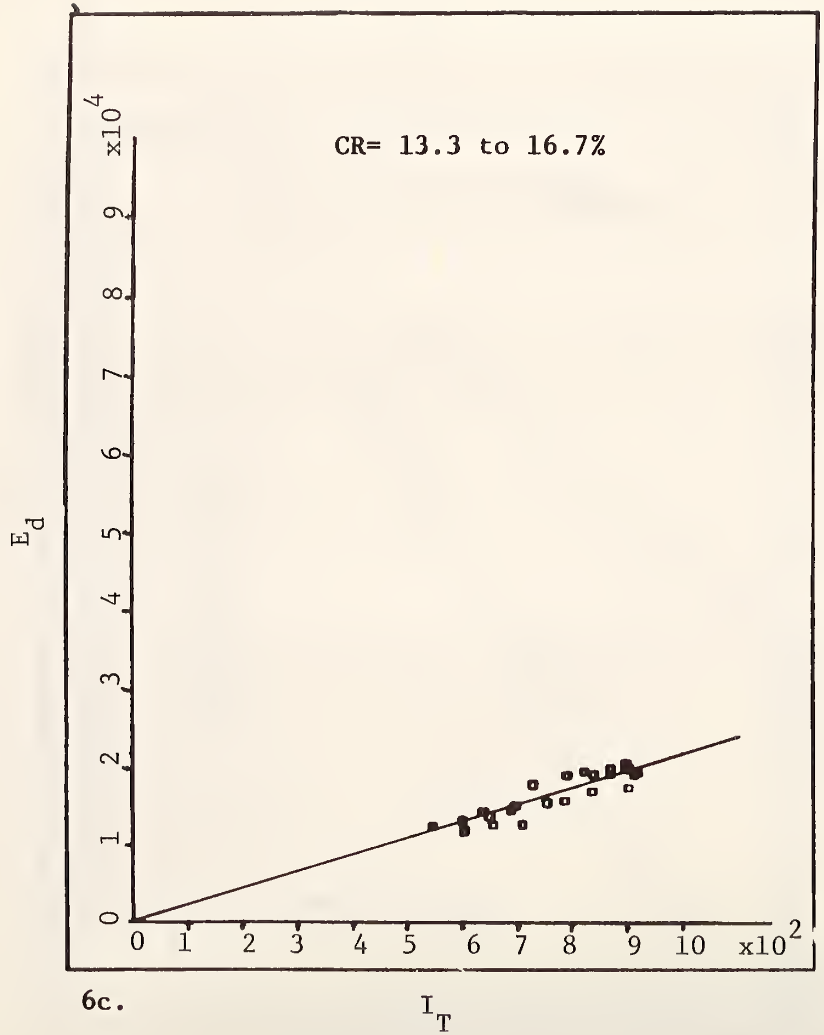
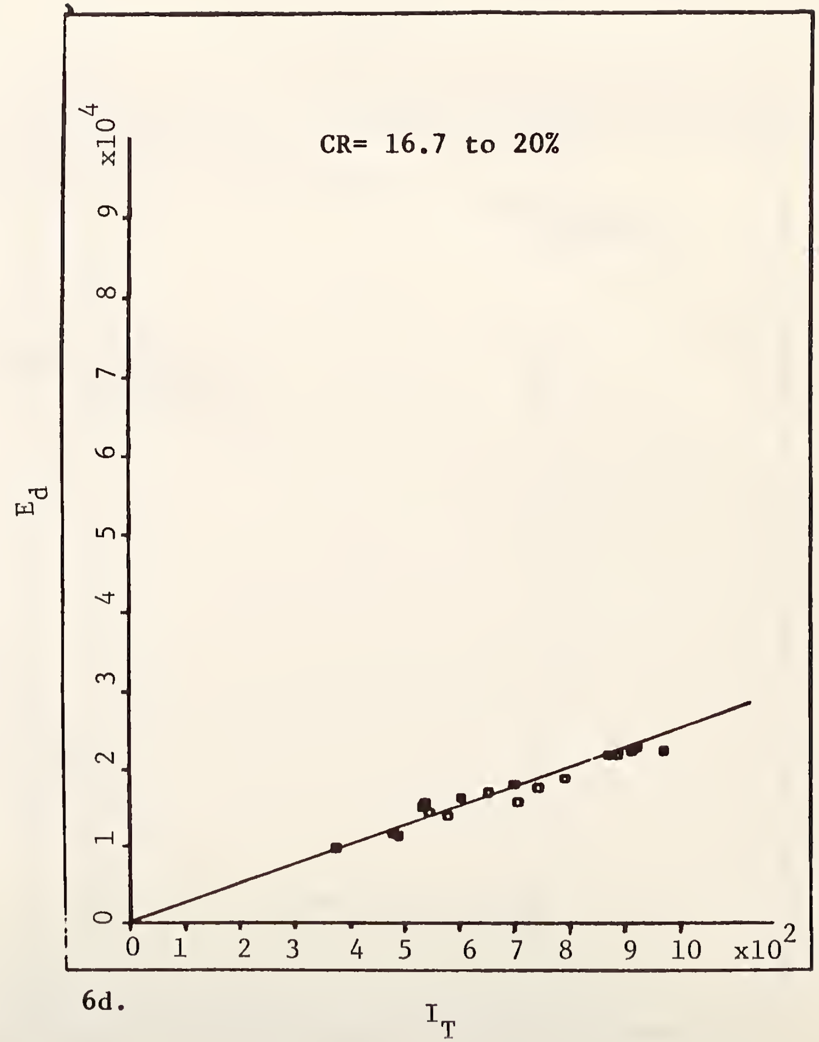


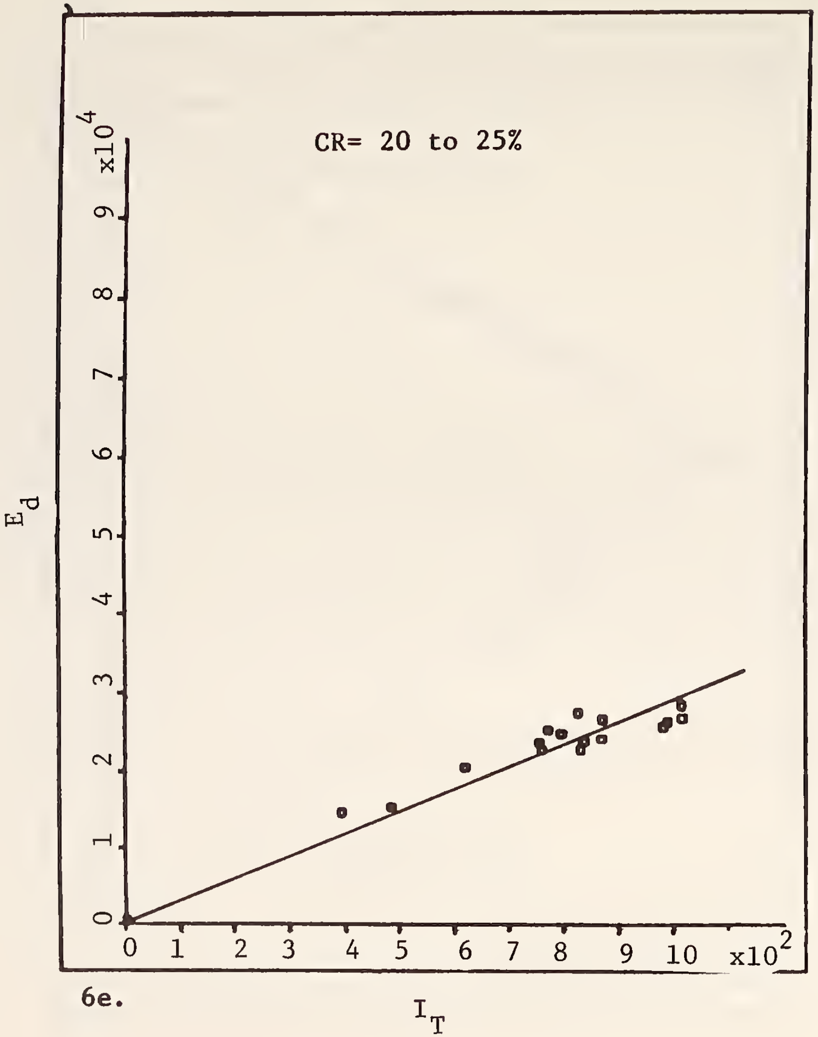
Figure 6. Diffuse illuminance (E_d) as a function of total irradiance (I_T) and cloud ratio (CR)



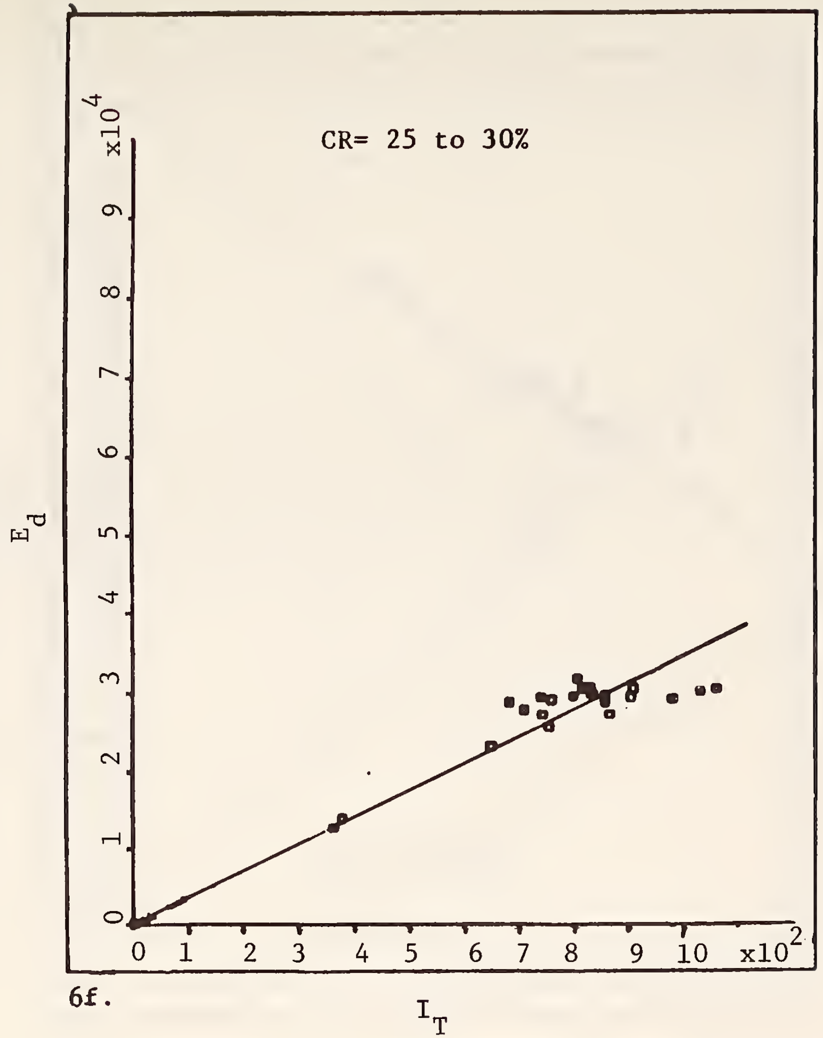
6c.



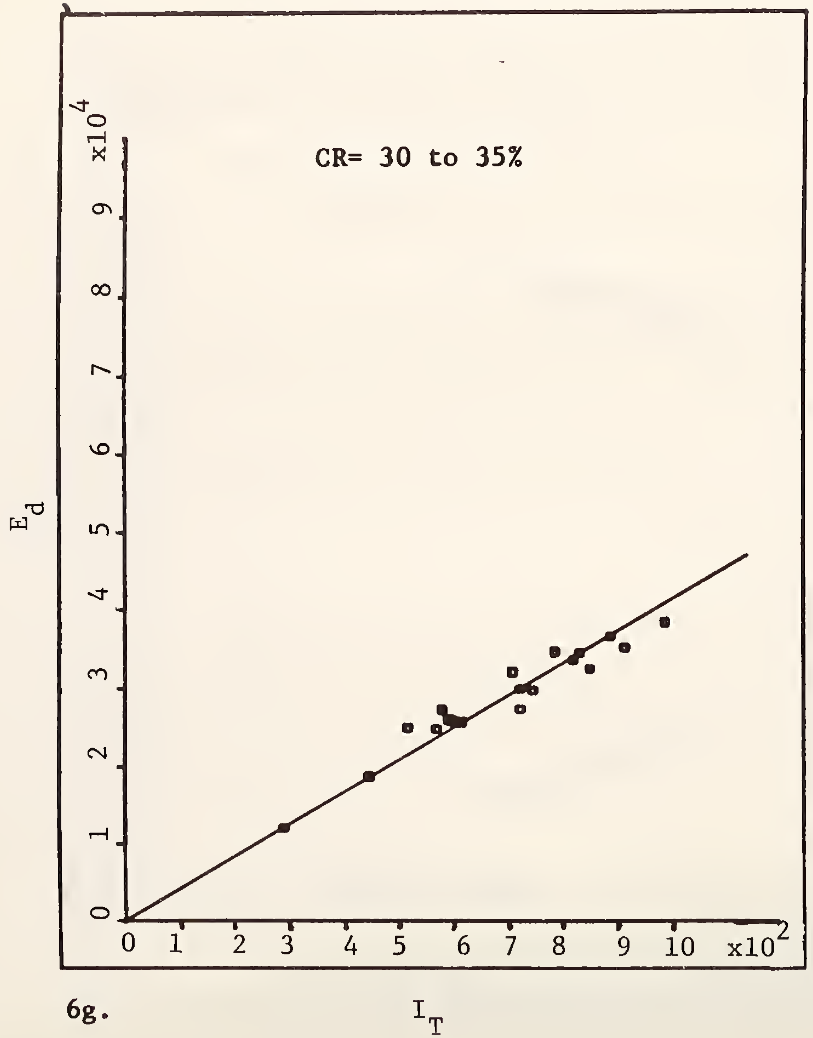
6d.


CR= 20 to 25%
E_d
$x10^4$
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9 10 $x10^2$
I_T

6e.

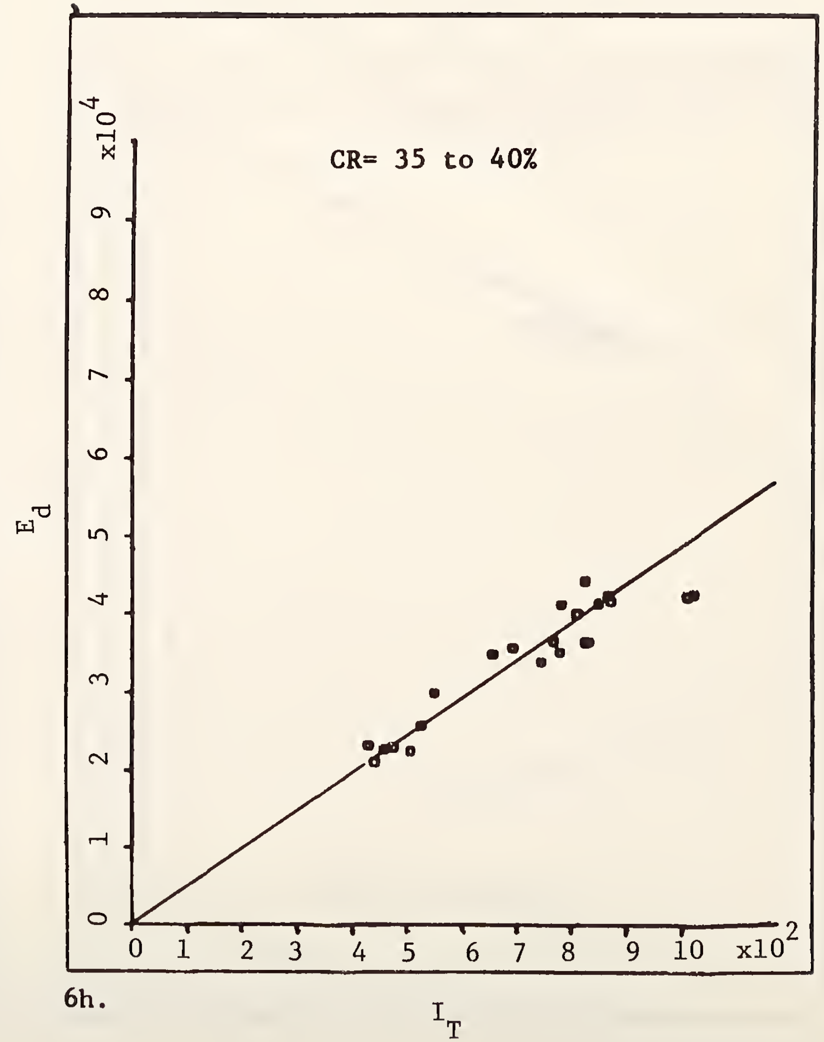

CR= 25 to 30%
E_d
$x10^4$
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9 10 $x10^2$
I_T

6f.



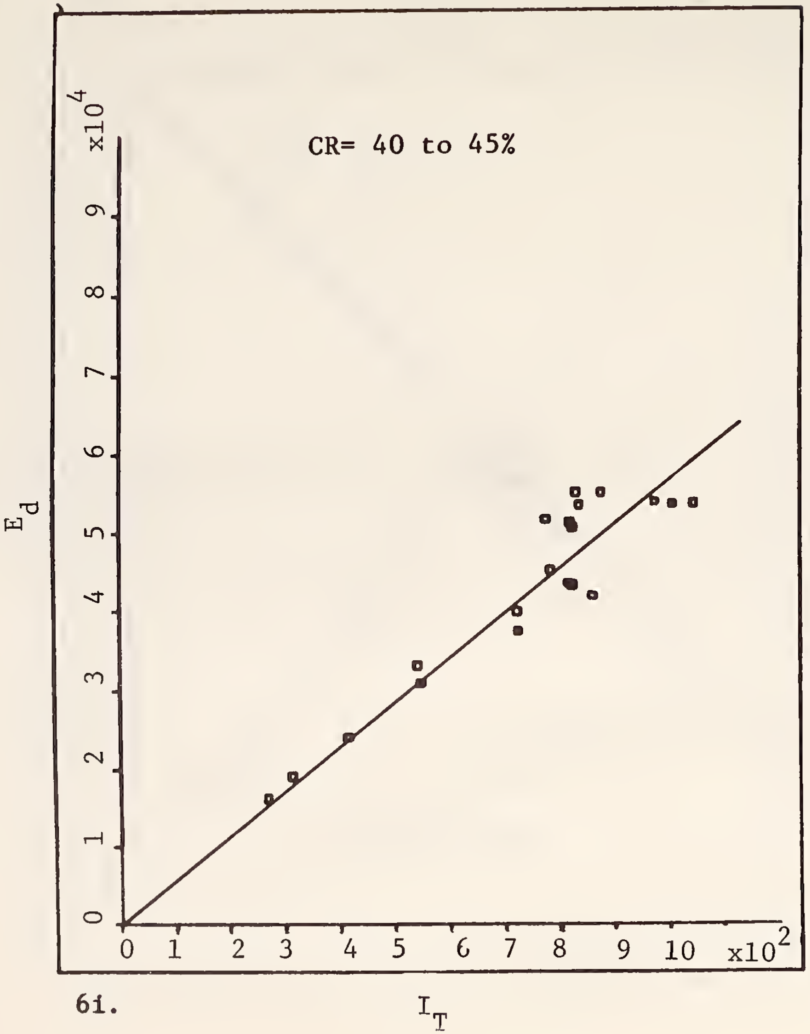
CR= 30 to 35%
E_d
$\times 10^4$
0
1
2
3
4
5
6
7
8
9
10
$\times 10^2$
I_T

6g.

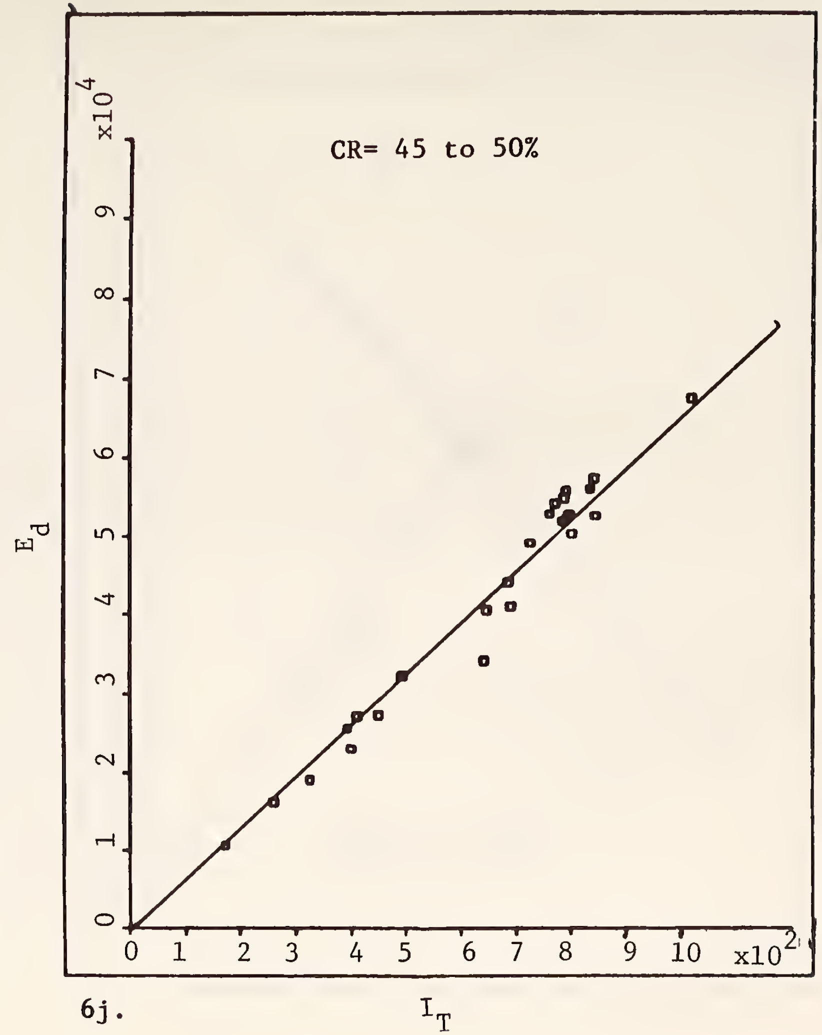


CR= 35 to 40%
E_d
$\times 10^4$
0
1
2
3
4
5
6
7
8
9
10
$\times 10^2$
I_T

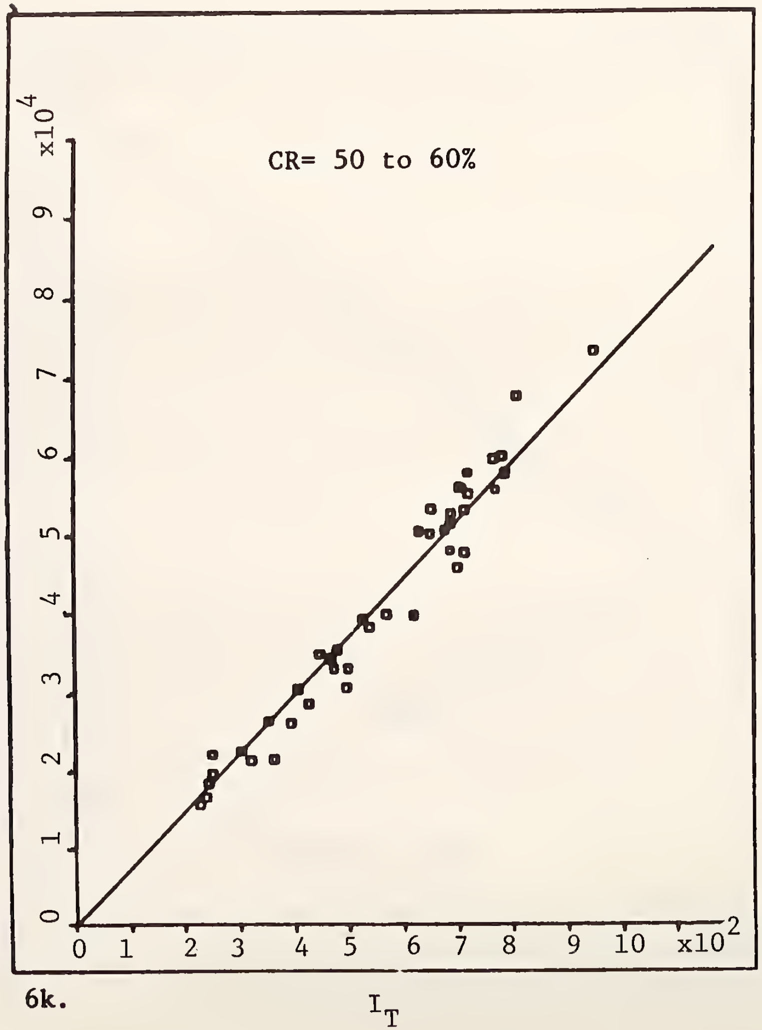
6h.



6i.

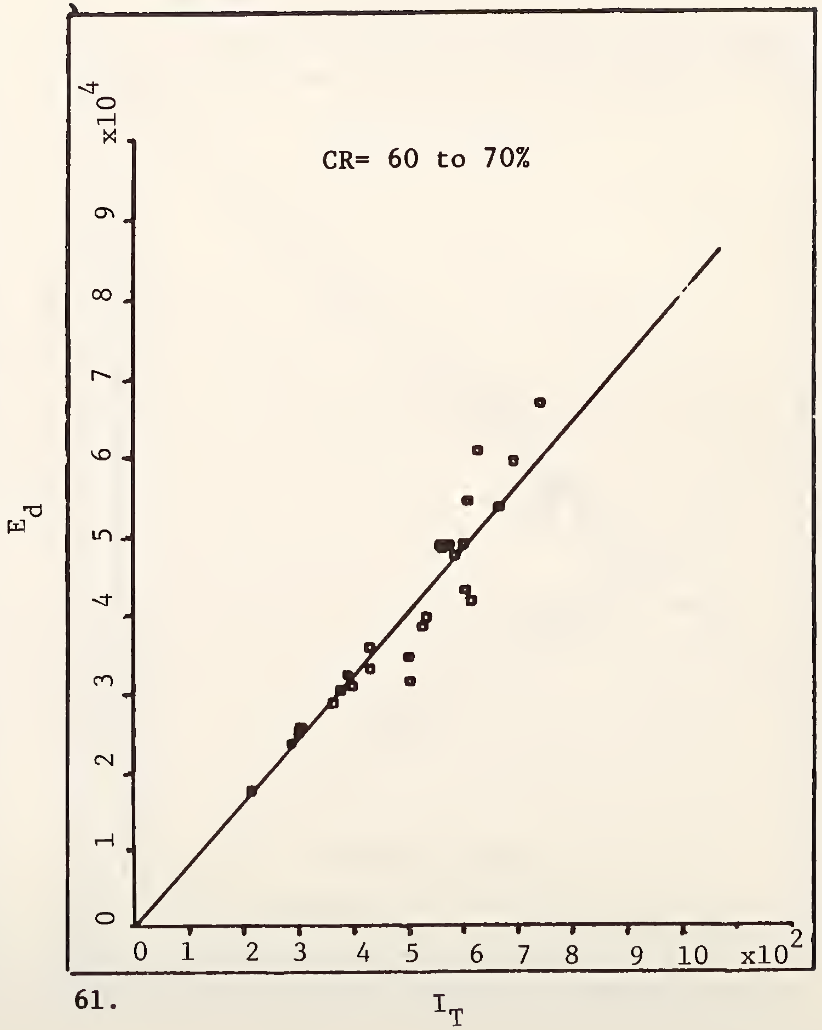


6j.



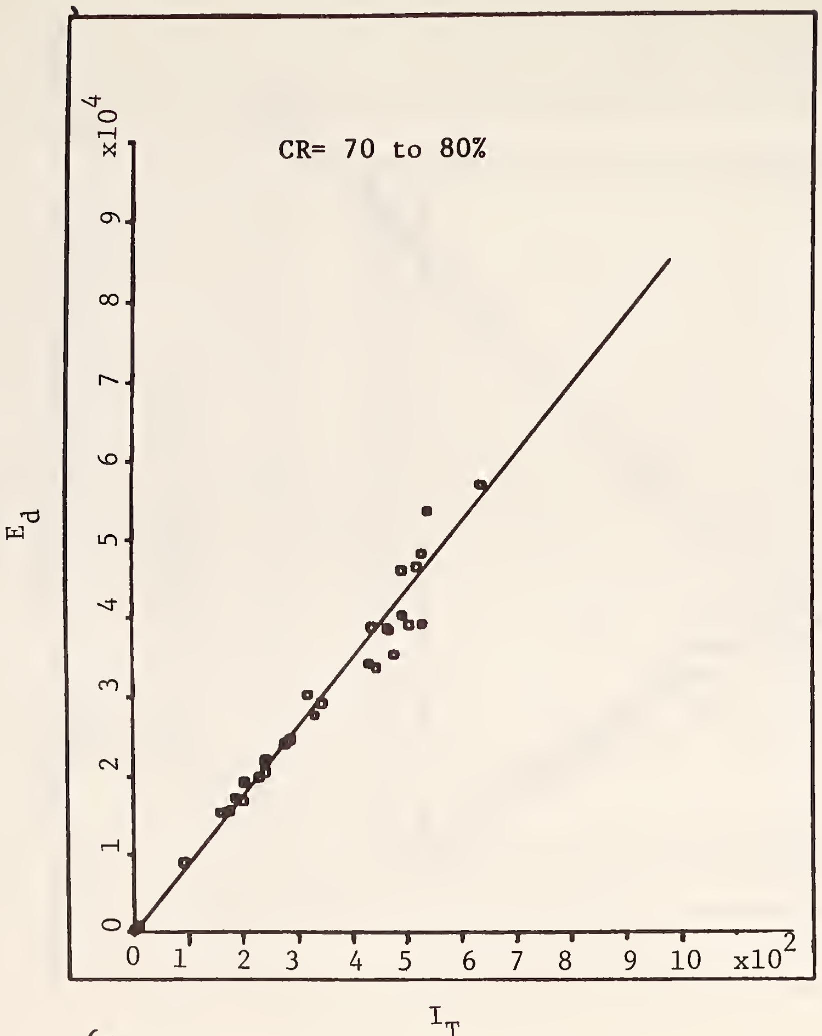
CR= 50 to 60%
E_d
x10^4
0
1
2
3
4
5
6
7
8
9
I_T
x10^2
10

6k.

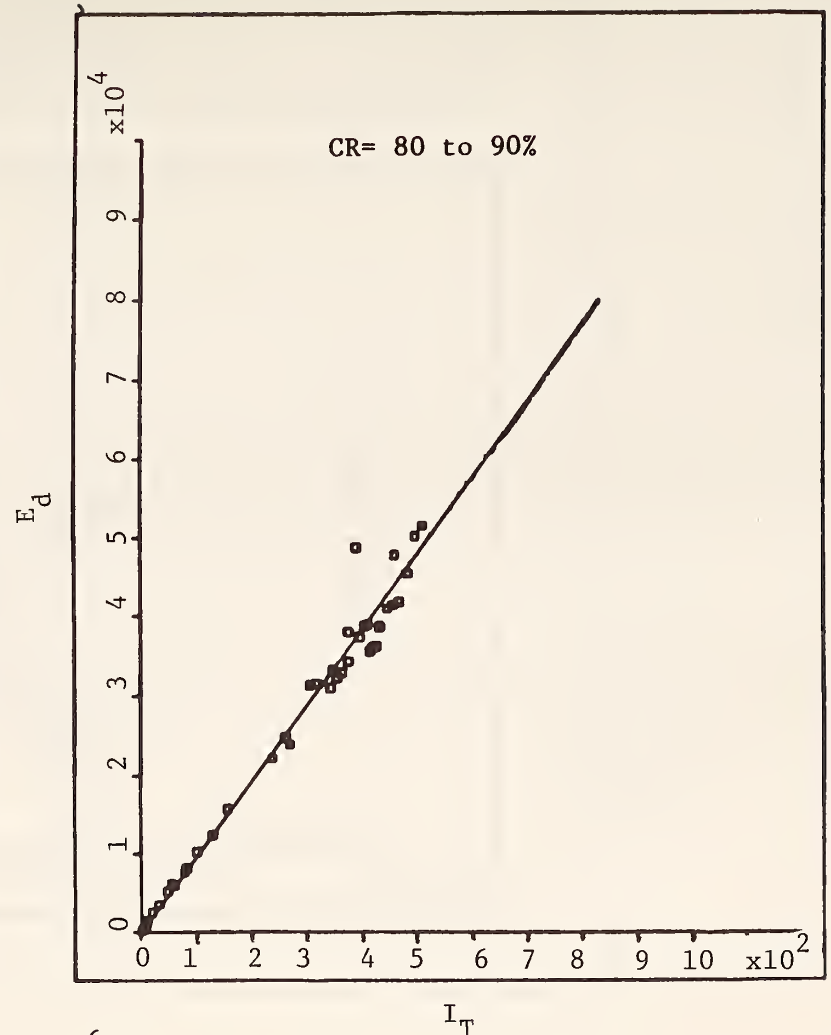


CR= 60 to 70%
E_d
x10^4
0
1
2
3
4
5
6
7
8
9
I_T
x10^2
10

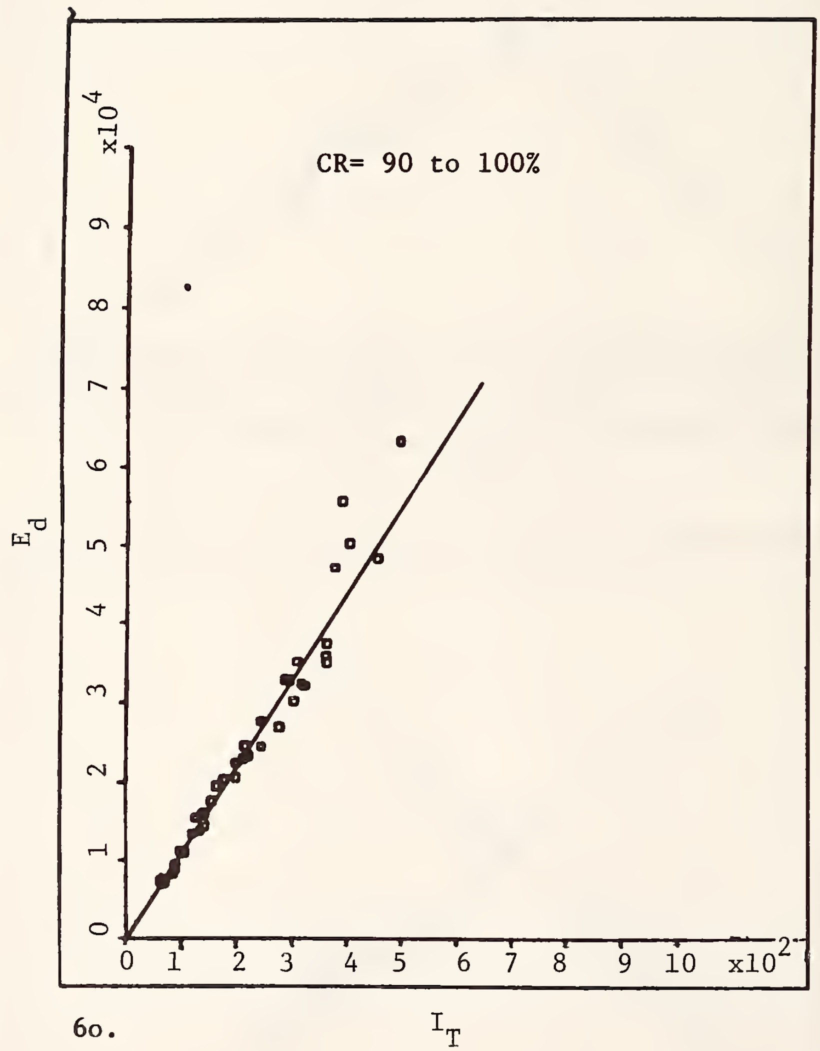
61.


CR= 70 to 80%
E_d
x10^4
0 1 2 3 4 5 6 7 8 9
I_T
0 1 2 3 4 5 6 7 8 9 10 x10^2

6m.


CR= 80 to 90%
E_d
x10^4
0 1 2 3 4 5 6 7 8 9
I_T
0 1 2 3 4 5 6 7 8 9 10 x10^2

6n.



6o.

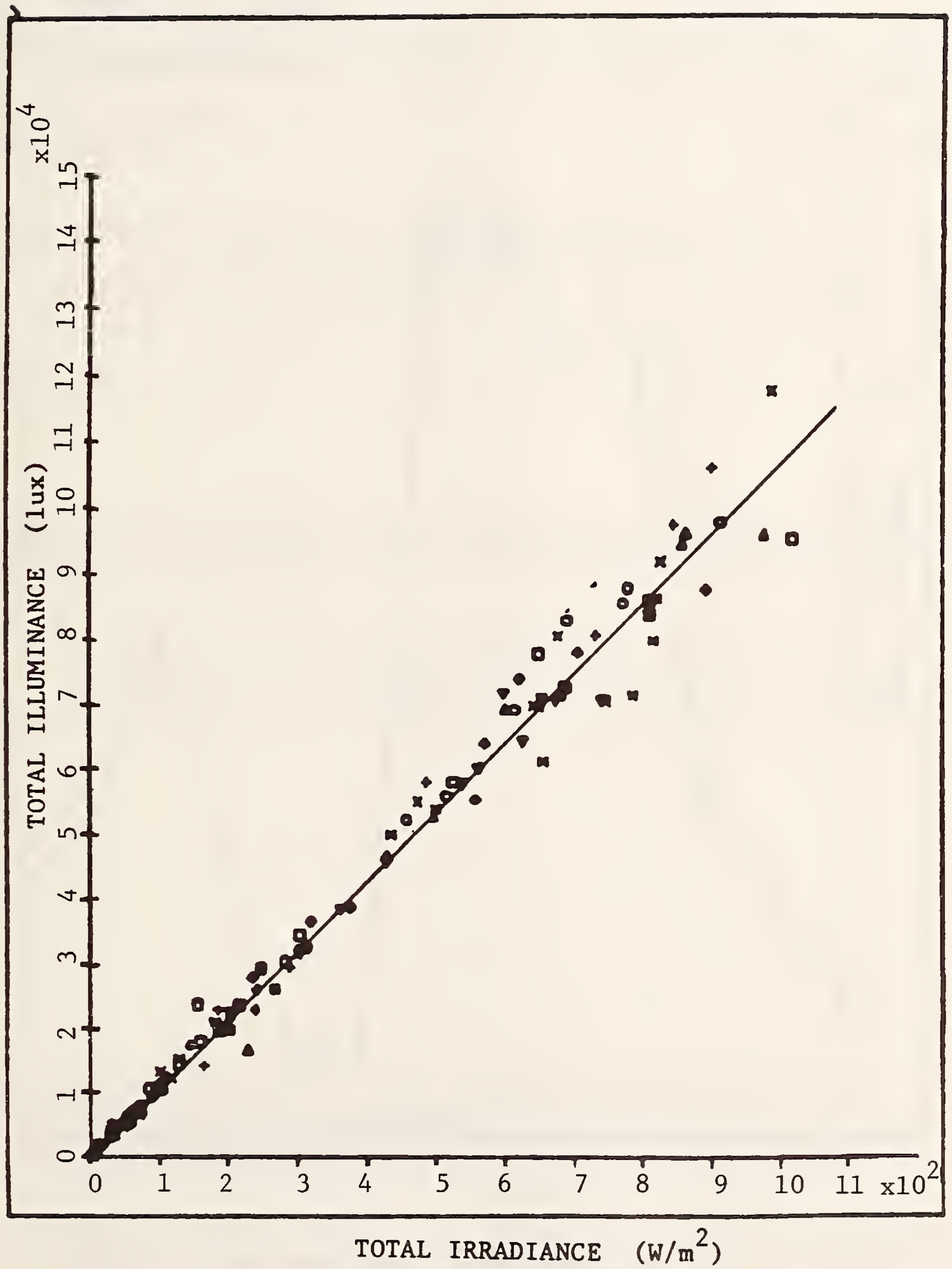


Figure 7. Total Illuminance as a Function of Total Irradiance

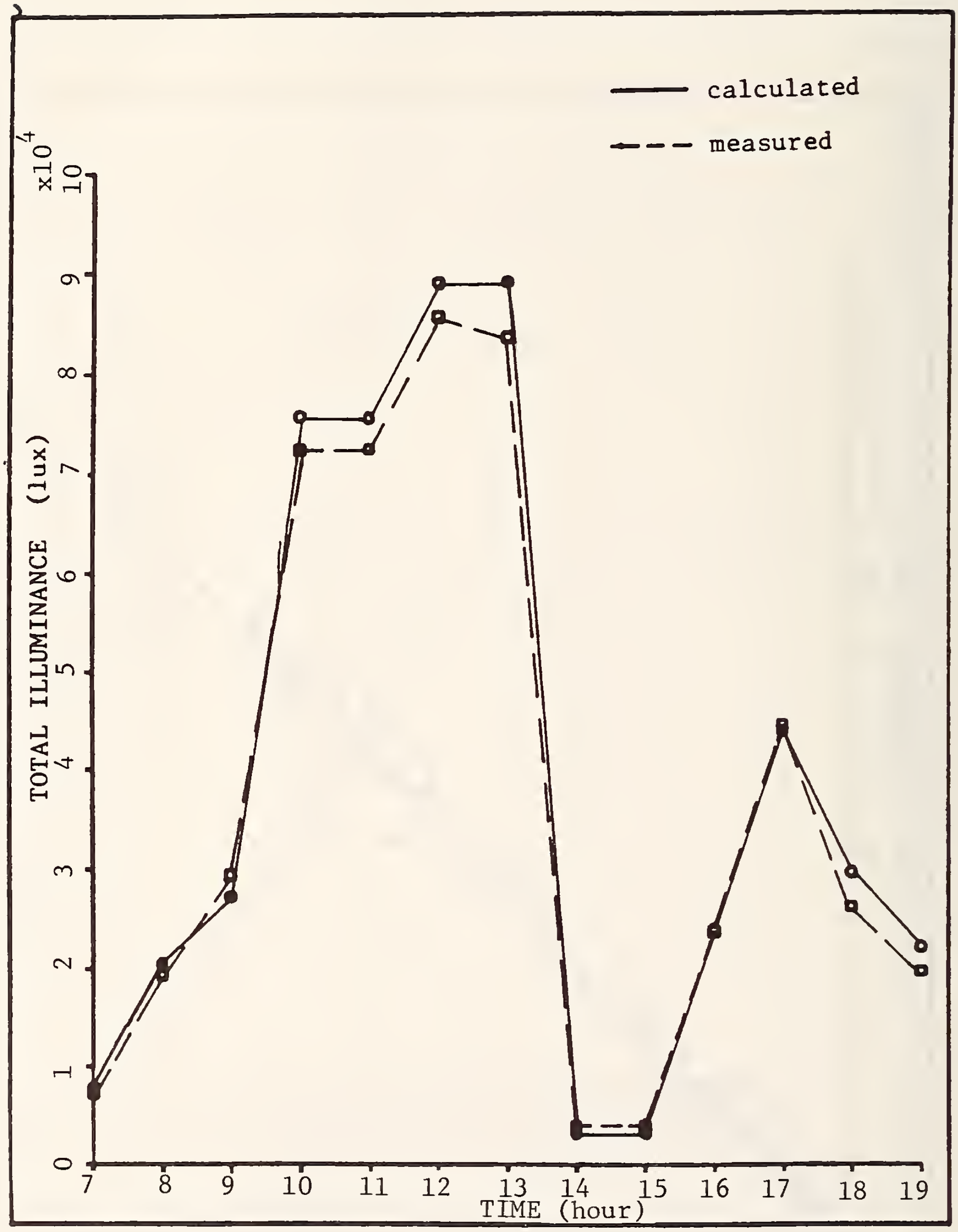


Figure 8. Total Illuminance - Measured vs. Calculated

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Experimental data were collected and analyzed under various cloud cover conditions to establish the relationship between solar irradiance and illuminance. Empirically derived equations are presented for estimating diffuse and total illuminance as a function of total and diffuse solar radiation.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

daylighting; illuminance; illumination; irradiance; solar radiation

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